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Technical Memorandum

Techniques for Minimizing Errors in Strain Measurements on WECS Rotors

J.G. Keller

May 1985

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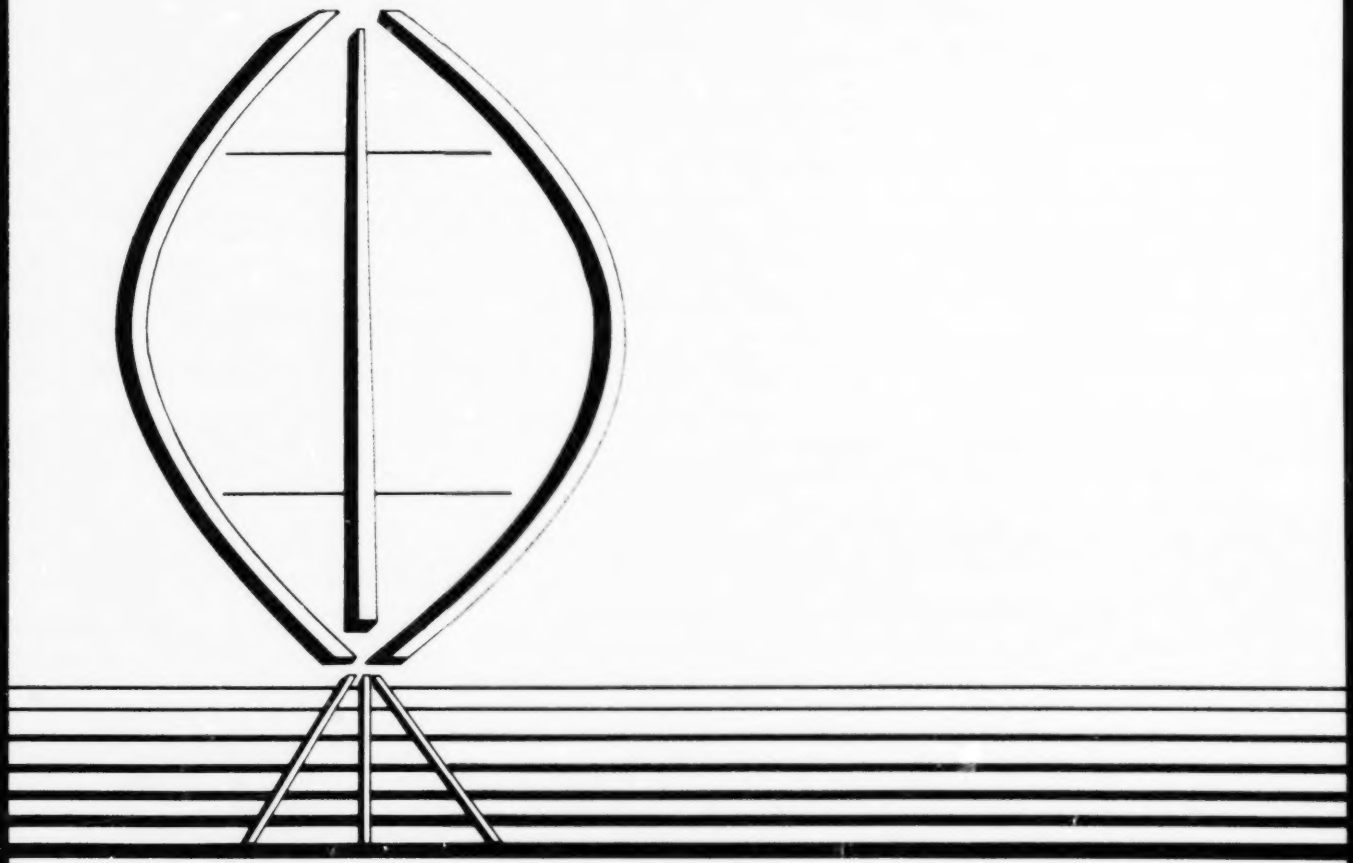

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TECHNIQUES FOR MINIMIZING ERRORS IN STRAIN MEASUREMENTS ON WECS ROTORS

J.G. Keller

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SUMMARY

Accurate determination of dynamic strain, and hence dynamic stress levels, is an important aspect of testing prototype wind energy conversion systems (WECS). Such data are used to ensure safe operating stresses and to predict fatigue life of critical elements of the structure. Strain measurements are also necessary for validating design methods, and particularly for confirming resonant modes and frequencies.

The following set of notes was compiled to explain the different types of errors encountered in strain gauge measurements. The report divides the different types of errors into sections. Each section discusses various errors and explains methods to reduce them. Throughout the report theoretical calculations are given and compared with data from instrumentation installed on the Aquilo machine, a 500 kW wind turbine being tested at the Atlantic Wind Test Site in Prince Edwa d Island. Along with the various errors found in strain gauge measurements, recommendations for future installations are also given.

RÉSUMÉ

La détermination précise de la déformation dynamique et, partant, de la charge dynamique est un élément important de l'essai des prototypes de systèmes de conversion de l'énergie éolienne. Ces données sont utilisées pour maintenir les contraintes de fonctionnement dans des limites sécuritaires et pour prévoir la durée de vie des principaux éléments de la structure. Les mesures de déformation sont aussi nécessaires pour valider les méthodes de conception et, plus particulièrement, pour confirmer les modes et les fréquences de résonance.

Les notes suivantes ont été préparées dans le but d'expliquer les différents types d'erreurs commises dans les mesures de déformation. Le rapport est divisé en sections, chaque section étant consacrée à un type d'erreur. Les différentes erreurs et des méthodes pour les réduire sont expliquées. Les calculs théoriques sont présentés et démontrés avec les mesures effectuées sur l'éolienne Aquilo, une turbine de 500 kW qui fait actuellement l'objet d'essais au Laboratoire d'essais éoliens de l'Atlantique (Î.-P.-E.). En plus des diverses erreurs accompagnant les mesures de déformation, le rapport donne des recommandations pour des installations futures.

TECHNIQUES FOR MINIMIZING ERRORS IN STRAIN MEASUREMENTS ON WECS ROTORS

J.G. Keller

1.0 INTRODUCTION

Accurate determination of dynamic strain, and hence dynamic stress levels, is an important aspect of testing prototype wind energy conversion systems (WECS). Such data are used to ensure safe operating stresses and to predict fatigue life of critical elements of the structure. Strain measurements are also necessary for validating design methods, and particularly for confirming resonant modes and frequencies.

The errors involved in strain measurements can be extremely small if care is taken in the selection, mounting, and operation of the bridges. Known errors such as those caused by lead resistance can be eliminated during the measurement. The following paragraphs analyze some of the errors found in strain measurements and also discuss how to reduce these errors by careful selection and placement of components.

2.0 STRAIN GAUGE BRIDGE MOUNTING AND PROTECTION

Before a proper understanding of possible errors in strain measurements can be realized, the construction of the sensor must be well understood. Figure 1 shows a typical strain gauge bridge mounted on a structure. The corresponding circuit diagram is also shown. The bridge consists of two active and two passive arms. The passive or inactive arms are mounted on a separate but similar piece of metal to that being measured so that there is no strain, but effects of temperature of the measurement metal are compensated, cancelling these errors in the active arms (see Section 4.0). The two active arms are directly mounted on the measured metal. Figure 2 shows the general construction of the bridge mounting with its various protective coatings. The system of protection shown here is more elaborate than that required in some installations but ensures a longer expected lifetime of the gauges. Less involved protection, as used on Aquilo, ends by covering the foil with protective tape. This has the advantage of keeping the profile of the bridge low, which is important on aerodynamic structures such as blades. Keeping the bridge absolutely waterproof is the prime importance of the protective coatings. Water penetrating the gauge area renders the bridge useless. The foil both reduces the noise pick-up by the gauge and provides an impervious vapour barrier, preventing moisture penetrating the gauge area. It is also important that the gauge area does not receive abrasive action or physical abuse (i.e., people walking on it).

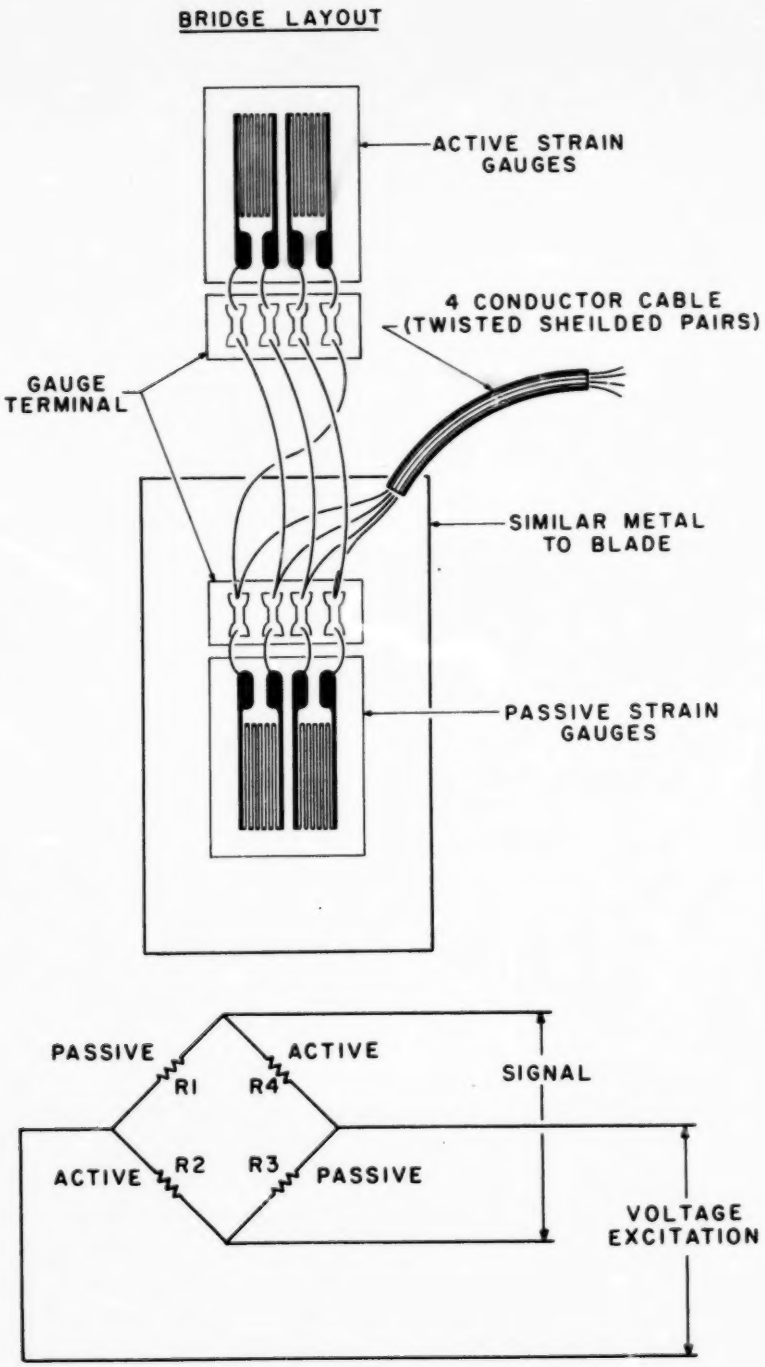


Fig. 1. Strain bridge installation and circuit diagram

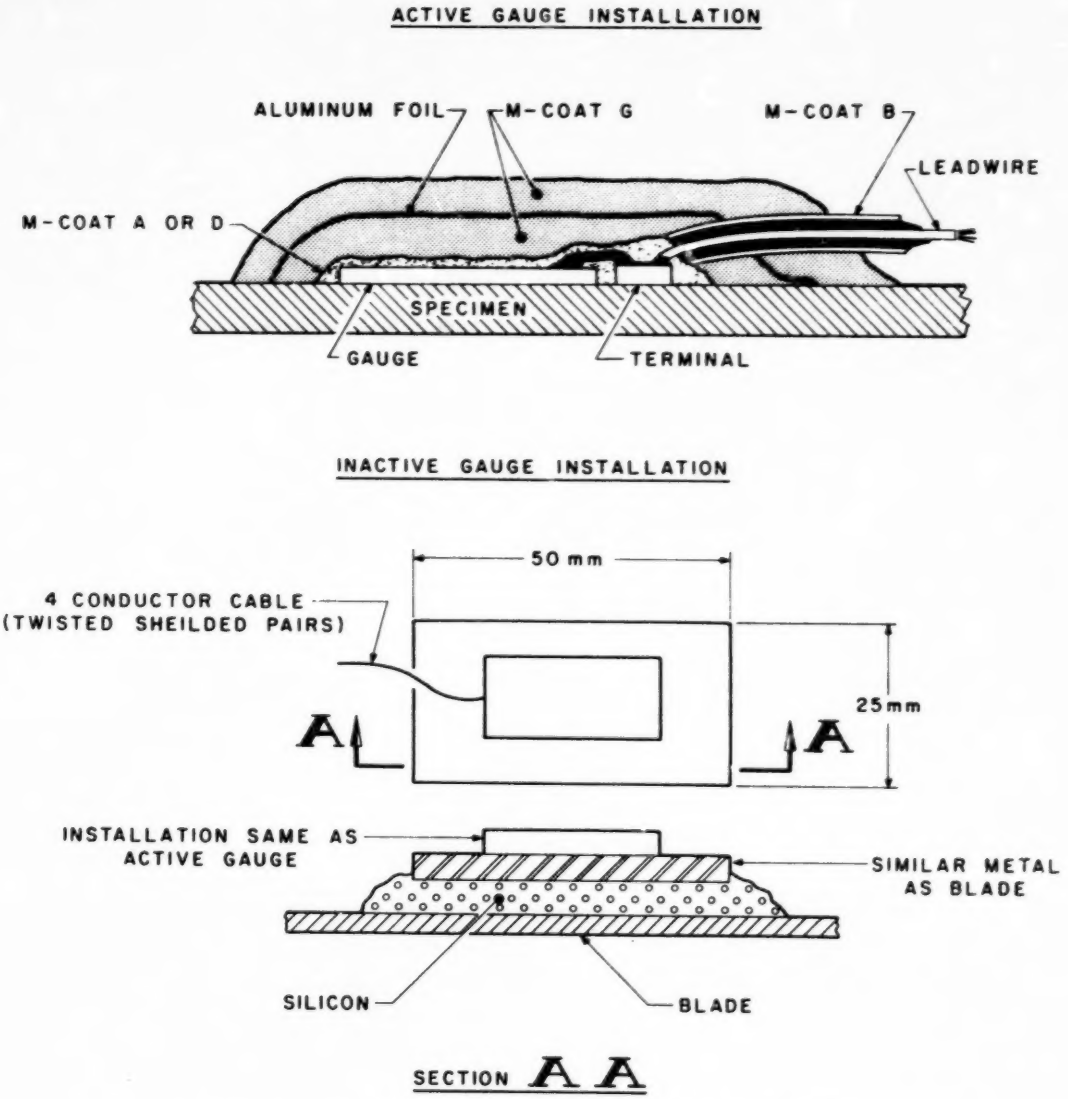
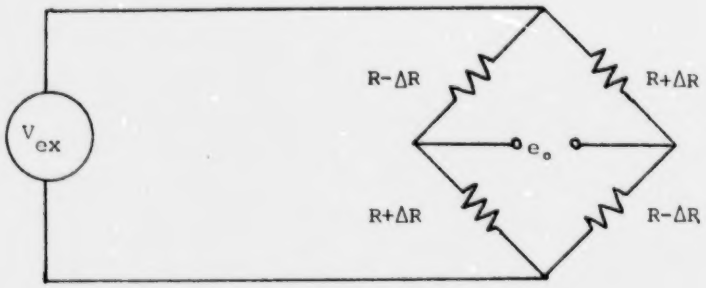


Fig. 2. Gauge installation on a blade surface

3.0 OUTPUT ERRORS DUE TO BRIDGE RESISTOR MISMATCH

Resistor mismatch creates an output offset due to the fact that individual resistor elements cannot be manufactured to an exact resistance value. There is always some finite tolerance within which resistors are cut. The offset can be significant, so care should be taken that offset adjustments are designed large enough to "zero" or balance the bridge before the amplifier circuit. This can be reduced significantly by

requesting elements manufactured in the same batch. Same-batch elements have much smaller resistance differences. The analysis of the possible offset is as follows:



Typical Bridge Circuit

If the resistors in the bridge have a tolerance of ±ΔR, then the range of e_o will be the following:

[1] $\quad e_o(max) = V_{ex}(\Delta R/R), \qquad e_o(min) = V_{ex}(-\Delta R/R)$

Changes in the overall arm resistance are small and they do not affect the output e_o substantially. Therefore,

[2] $\quad$ possible e_o offset = $\pm V_{ex}(\Delta R/R)$

Example:

If we have a 120 Ω bridge using elements cut to ±0.1% (or 0.12 Ω) and an excitation voltage V_{ex} of 10.0 V, using equation [2], it is seen that the output voltage e_o will be uncertain by ±10 mV.

A zero offset adjust is usually required for these bridges. The offset adjust should be designed to balance the bridge to cover at least the expected offset from gauge tolerance and perhaps more if some tare strain need be eliminated. Note that "arm shunting" balancing method can reduce the active arm's effective gauge factor, a source of error if not accounted for.

4.0 OUTPUT ERRORS DUE TO TEMPERATURE COEFFICIENTS

The resistor elements of the bridge have temperature coefficients and expansion coefficients which, when they are glued to the measured metal, cause the zero offset of the bridge to change with temperature. To reduce this error, manufacturers supply gauges with known expansion coefficients

which closely match those of commonly used metals. The purchase of gauges which have expansion coefficients similar to that of the measured metal ensures that the gauges do not measure undesired strain due to temperature expansion/contraction of the measured metal. However, the gauges usually track the metal over a small temperature range and always have some small, but finite error.

To reduce this error even further, both the inactive or passive arms and the active arms of the bridge should use similar gauge elements. Thus, each arm has a very similar temperature and expansion coefficient. If the passive arms have the same sensitivity to temperature as the active arms, signal components will cancel and not show up at the output. This is achieved by mounting the inactive and active elements close together. While it is important that the inactive gauges undergo the same strain due to temperature-induced expansion as the active gauges to cancel these errors, it is also important that the inactive gauge does not measure any other real but unknown strain on the measured metal. This would introduce new errors in the measurement. To eliminate this possibility, the inactive bridge arms are usually mounted on a separate piece of similar metal which is mounted "floating" on the measured metal (see Figure 2). This floating piece is subject to no strain but stays close to the measured metal temperature, correcting for temperature-induced errors.

In cases such as on beams in which simple bending is taking place and the opposite surfaces are at the same temperature, two strain gauges can be installed directly opposite each other to perform one half of the bridge function (1). In this case the two gauges compensate each other as well as measure the strain (with double the output). Similarily, it is possible to mount gauges 90° to each other on shafts to measure torque (45° to the longitudinal axis) and on beams in purely tension/compression mode. In these cases temperature compensation can be achieved by mounting the inactive gauge directly on the measured material. In the latter case, however, of the beam in tension, the Poisson strain must be accurately known to achieve an accurate signal. In all these cases where compensating gauges are mounted directly on the measured metal, caution is advised to ensure that the compensating gauge is not measuring erroneous strain caused by an unknown stress mode. On any structure that has a complex shape such as a blade structure, it is imperative that the dummy gauges are mounted on a separate piece of similar metal and mounted on the measured material, keeping its temperature as close to that of the measuring gauges as possible.

Because of the silicon barrier between the measured metal and the inactive gauges and self-heating of the gauges, there can be a finite temperature difference between the resistor elements. Since the resistor

elements have temperature coefficients, there is a subsequent small resistive difference. This affects the output e_o directly. Usually this error is extremely small. However, care should be taken that the electrical insulating barrier on the inactive elements is an excellent heat conductor and thin to keep element temperatures as close as possible. Keeping self-heating to a minimum by using higher resistance gauges also reduces this problem significantly (see Section 5.0).

Differences in actual element temperature coefficients can also be a problem. For example, if the resistors have a temperature coefficient of ±5 ppm/C°, this means that in the worst case one element of the arm can increase in resistance by 5 ppm/C° while the other element can decrease by 5 ppm/C°. The resulting error is V_{ex} = ΔR/R ppm/C°. Using the previous example of 10.0 V excitation this means the output can change ±50 μV/C°. Over a 20°C span, the output could vary by ±1 mV. Again this is a substantial amount for a device whose maximum output is ±15 mV. In practice, however, elements usually track each other to within a few parts per million. Thus the error due to different temperature coefficients is usually very small. This error can also be minimized by purchasing elements from the same batch number, which ensures a good temperature coefficient match between elements.

5.0 CALCULATION OF SELF-HEATING OF STRAIN SENSORS

Self-heating of the strain gauge causes increased errors in the strain signal. Additional strain is seen between the sensor and the metal surface due to a temperature gradient caused by gauge self-heating. This self-heating is proportional to the number of watts dissipated by the bridge, its area, and the heat dissipation properties of the metal being measured. The power dissipation is equal to the square of excitation voltage V_{ex} divided by the bridge resistance.

[3] $$P = V_{ex}^2/R$$

where

P = the power dissipated by the bridge (watts)
R = bridge resistance (ohms)
V_{ex} = bridge excitation voltage (volts)

The active area of the bridge can be found in the gauge description. One must remember that each bridge is constructed of four arms. Usually catalogue descriptions are for each arm.

Example:

The typical 120 Ω gauge used both on the Aquilo and the Iles de la Madeleine WECS was the CEA-13-250-UW120 device. This device had an active grid area per arm of 6.35 mm × 4.57 mm, or 29.02 mm^2.

The bridge excitation voltage V_{ex} was 10.0 V. Therefore,

$$P = V_{ex}^2/R$$
$$= 10.0^2/120$$
$$= 0.833 \text{ W}$$

Each sensor dissipates 0.833/4 or 0.208 W.

The power density at a gauge can be calculated by dividing the power by the appropriate area.

[4] $$P_d = 1000P/A = \frac{1000 \times 0.208}{29.02} = 7.176 \text{ kW/m}^2$$

where

P_d = power density (kilowatts/square metre)
A = active bridge area (square millimetres)
P = power dissipated by the bridge (watts)

Table 1 (from ref. 1, Tech Note TN-502) shows the relation between accuracy requirements and permissable self-heating power density. From Table 1 it can be seen that the error due to self-heating of the example gauge is fairly small. The power density for aluminum of 7.2 kW/m^2 shows a high accuracy will result (<3% error).

Errors due to self-heating can be substantially minimized by purchasing the highest resistance gauge possible to suitably fit on the measurement surface. The industry standard is now 350 Ω gauges. Since the power consumed by the gauge is inversely proportional to its resistance, going from 120 Ω gauges to 350 Ω gauges would reduce self-heating power density to less than one-third, since the active area on higher resistance gauges is usually greater. Higher resistance gauges also have reduced power consumption, which translates into smaller power supplies and lower errors due to lead resistances. This will be discussed in the following sections in more detail.

Table 1. Permissible self-heating power density for various accuracy requirements on various structure materials (kW/m^2) (information taken from ref. 1, Tech Note TN-502)

	EXCELLENT	GOOD	FAIR	POOR	VERY POOR
Accuracy require-ments	Heavy aluminum or copper specimen	Thick steel	Thin stainless steel or titanium	Filled plastic such as fibreglass/ epoxy	Unfilled plastic such as acrylic or polystyrene
STATIC:					
High(<3%)	3.1-7.8	1.6-3.1	0.78-1.6	0.16-0.31	0.016-0.031
Med.(3-5%)	7.8-16	3.1-7.8	1.6-3.1	0.31-0.78	0.031-0.078
Low (>5%)	16-31	7.8-16	3.1-7.8	0.78-1.6	0.078-0.16
DYNAMIC:					
High(<3%)	7.8-16	7.8-16	3.1-7.8	0.78-1.6	0.016-0.078
Med (3-5%)	16-31	16-31	7.8-16	1.6-3.1	0.078-0.31
Low (>5%)	31-78	31-78	16-31	3.1-7.8	0.31-0.78

6.0 CALIBRATION USING A RESISTOR SHUNT (R_{cal})

The output of a strain gauge bridge with two active gauges on opposite sides due to direct physical load (compression), is as follows:

[5] $$e_o = V_{ex}\, GS/(2 - GS)$$

where

V_{ex} = bridge excitation voltage (volts)
G = gauge factor
S = the strain applied

Example:

The output for 250 με (με = microstrain) on the typical bridge used on Aquilo would be as follows:

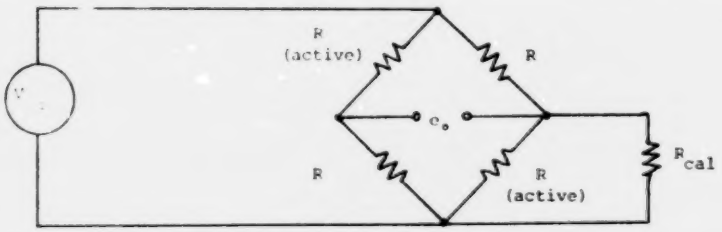
$$e_o = 10 \times 2.1 \times 250 \times 10^{-6}/(2 - 2.1 \times 250 \times 10^{-6})$$
$$e_o = 2.6257 \text{ mV}$$

In aluminum a strain of 250 με corresponds to a stress of approximately 2500 psi.

A calibration resistor is often chosen to be placed temporarily in parallel with one arm of the bridge to simulate a known strain, thereby to confirm the gain of the signal conditioner. This resistor is commonly referred to as R_{cal}. The value of R_{cal} is dependent on the load/strain that it is desired to simulate. It is usually chosen to represent a high fraction of the expected measurement value (often 100%).

Example:

For Aquilo, a resistance was chosen to simulate approximately 250 με, which corresponds from the above calculation to 2.626 mV output.



V_{ex} = 10.00 V
R = 120 Ω
e_o = 2.6257 mV

[6] $$e_o = V_{ex}R/[4(R_{cal} + 0.5R)]$$

[7] $$R_{cal} = (V_{ex}\ R/e_o - 2R)/4$$

Using the above values from the Aquilo installation:

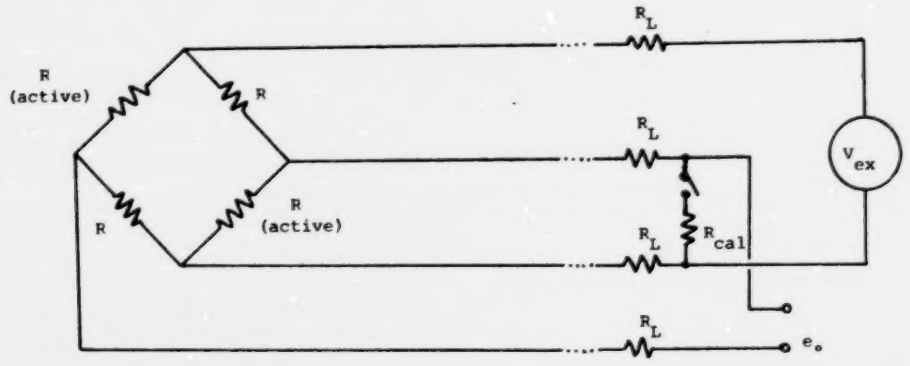
$$R_{cal} = (10 \times 120/2.6257 \times 10^{-3} - 2 \times 120)/4$$
$$= 114200\ \Omega$$

Assuming zero conductor resistance, a resistor of about 114.2 kΩ shunted in parallel with one of the arms will give an output equivalent to 250 με (e_o = 2.626 mV).

7.0 LEAD LENGTH ERRORS

Wind turbine rotors can be physically very large, and various constraints may dictate strain gauge leads being up to 100 m in length. There are two types of errors encountered when the sensors are mounted a long

distance from the measurement and calibration devices. Both errors are caused by resistance in the leads running to the bridge. This resistance can best be illustrated in the following schematic:



where

e_o = output voltage (volts)
R = bridge arm resistance (ohms)
R_L = lead resistance (ohms)
R_{cal} = shunt resistance (ohms)

The first type of error is in the actual measurement of strain while the second error is in the use of the calibration resistance R_{cal}.

7.1 Output Error due to Lead Resistance

This error originates from voltage drops in the excitation lines going to the bridge. The excitation voltage V_{ex} is usually set at a fixed value at the measurement end, so there will be a voltage drop along the leads to the bridge due to bridge current and lead resistance R_L. If the lead resistance is known, this potential drop can be calculated. Reduced V_{ex} at the bridge affects the output e_o directly. A 10% drop in V_{ex} at the bridge reduces the output e_o by 10% for the same strain. In general, the voltage excitation at the bridge, V_{ex}', can be calculated as follows.

[8] $$V_{ex}' = V_{ex}R/(R + 2R_L)$$

where

V_{ex}' = excitation voltage at bridge (volts)
V_{ex} = excitation voltage (volts)
R = bridge resistance (ohms)
R_L = lead resistance (ohms)

The error introduced by excitation voltage drop in the lead wires can be eliminated by various methods. The most obvious methods reduce the lead resistance to an acceptable level by increasing the wire size to the gauges and/or reducing the wire length between V_{ex} and the gauges (by moving the front-end amplifier and V_{ex} closer to the gauges). If these two methods are impractical other methods must be employed. One other method is to use a six-wire measurement. This involves using two leads to carry the bridge excitation current and two leads to sense the voltage excitation at the bridge. This way the excitation voltage is corrected so the error is eliminated. The disadvantage of this mehtod is the requirement for two extra leads for each bridge. This can be quite costly. Other correction methods involve estimating or measuring the lead resistance. Once this is known a correction can be applied either by adjusting gain factors or by increasing V_{ex} at the measurement device to compensate for the known voltage drop on the lead wires. Adjusting gain factors has the advantage of easily correcting the measurement device or data asquisition system. Gain adjustment can be made on the amplifier circuits but this makes each circuit unique, which can cause unwanted difficulties. Separate excitation voltage adjustments for each bridge can also be both costly and time-consuming and would also be unique to each bridge. Correcting gain factors by software is by far the easiest method. Another solution would be to use constant current excitation.

Example:

On the 500 kW VAWT Aquilo all the circuits are the same. Individual lead resistances are known. From these data gain corrections are applied in the computor software. This makes the correction extremely easy and allows all the amplifier/excitation circuits to be interchangeable. Table 2 illustrates the errors realized in the Aquilo installation. Using equation [8], actual excitation voltages at the bridges were calculated for each circuit. The gain correction used by the computor was calculated as follows:

$$[9] \qquad G' = G(R + 2R_L)/R$$

where

G' = corrected gain
G = normal gain with zero line resistance
R_L = line resistance (ohms)
R = bridge resistance (ohms)

For the aluminum structure of Aquilo, 1 με is equal to 10 psi. The last column in Table 2 lists the values used to correct the gains at the computer. See Figure 3 for the various locations of each station on the blades.

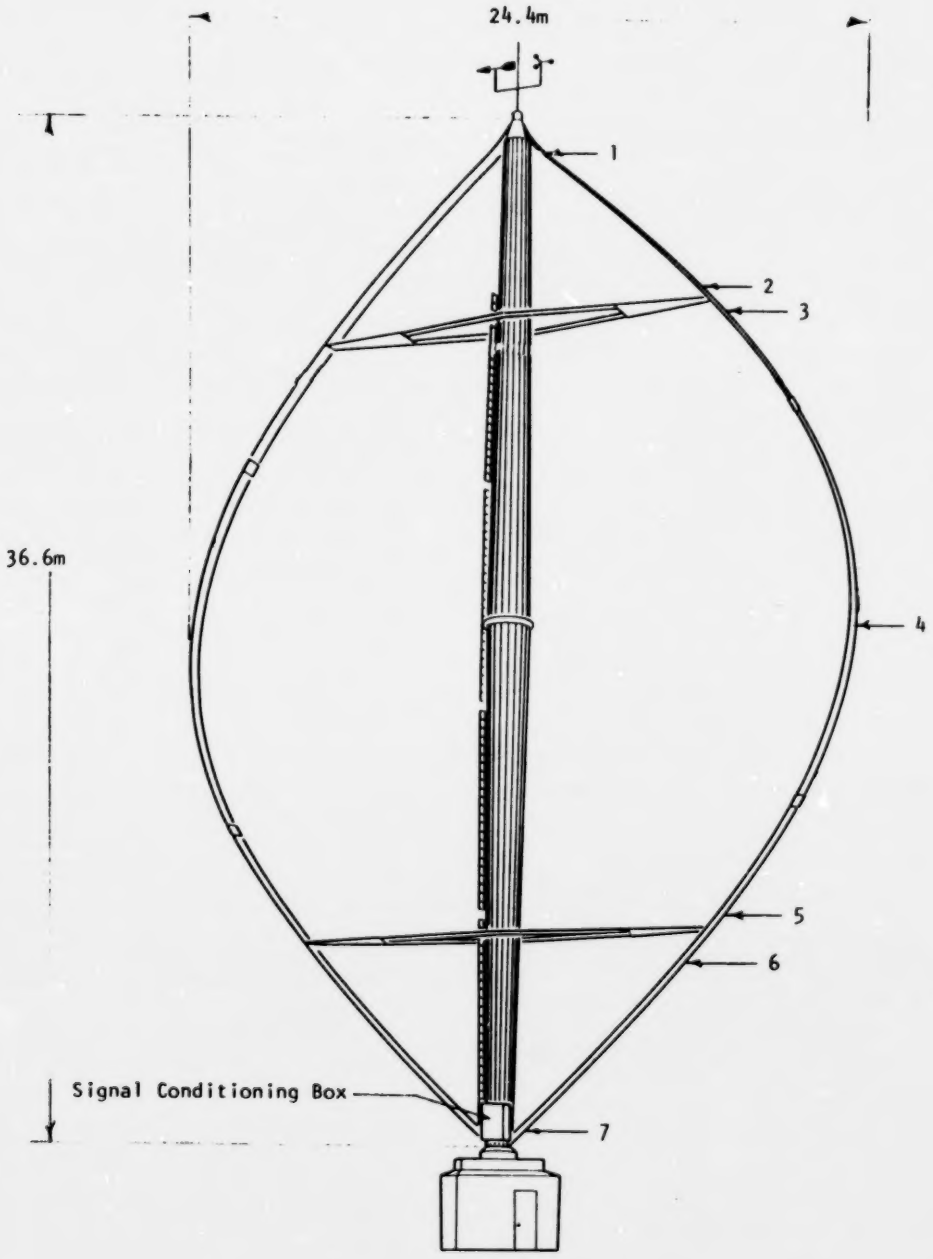


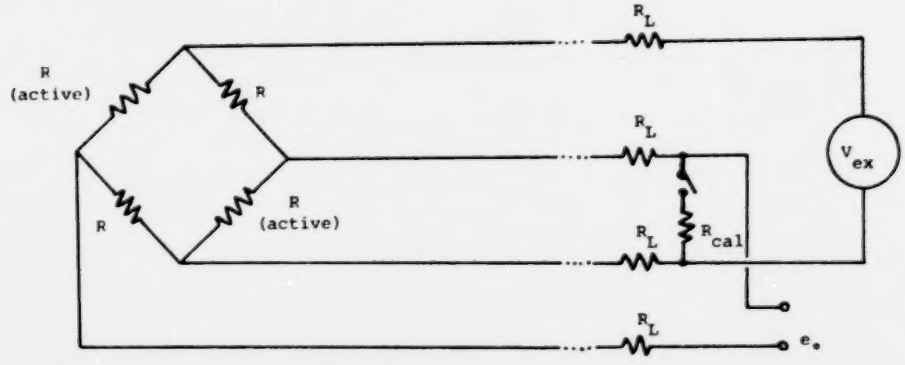
Fig. 3. Strain gauge locations on Aquilo

Table 2. Lead resistance data for Aquilo strain gauges

Station group	Lead resistance (Ω)	Excitation voltage, V_{ex} (V)	Calculated output for 250 με load (mV)	Calculated gain (corrected) psi/mV
1	2.3	9.631	2.529	988.6
3	1.9	9.693	2.545	982.3
4	1.3	9.788	2.570	972.8
5	0.7	9.884	2.595	963.2
6	0.7	9.884	2.595	963.2
7	0.2	9.968	2.617	955.3
	0.0	10.000	2.6257	952.13

7.2 R_{cal} Errors due to Lead Resistance

When the sensors are a long distance from the R_{cal} shunt, errors due to lead length resistance come into effect. Unlike in the case of lead resistance error on actual strain measurements where the bridge output is reduced, the bridge output actually increases due to lead resistance in the R_{cal} shunt lines.



where

R = bridge arm resistance (ohms)
R_L = lead resistance (ohms)
R_{cal} = calibration resistor (ohms)
V_{ex} = excitation voltage (volts)
e_o = output voltage (volts)

The exact derivation of the bridge output in this case is a very long and tedious computation (5) best solved numerically using a small computer program. Perino (3) has shown that these equations can be simplified to Equation [10]. The author has confirmed both methods are identical using a

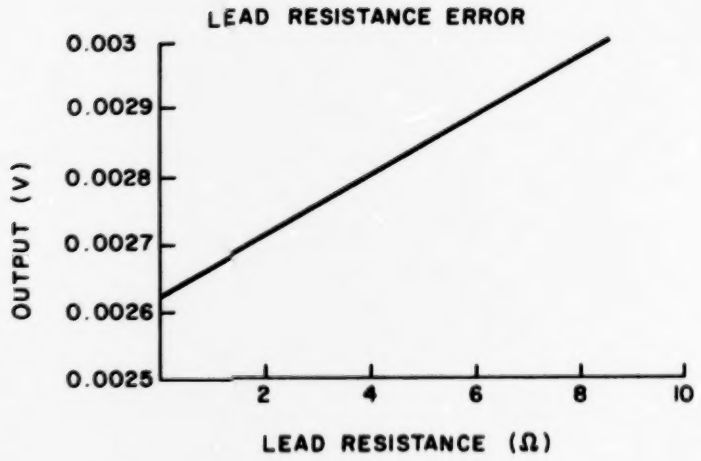


Figure 4. Output error

computer program. Figure 4 graphs the shunt calibration output changes with respect to the lead resistance, R_l. For this plot, V_{ex} = 10 V, R = 120 Ω, and R_{cal} = 114 200 Ω.

[10] $$e_o = (V_{ex}/2)[(R + 2R_L)/(R + 3R_L + 2R_{cal})]$$

The gain error caused by the lead resistance is as follows:

$$e_o/e_o' = \text{Gain error}$$

where

e_o = nominal output, R_L = 0 Ω
e_o' = output with $R_L > 0$

[11] $$e_o/e_o' = [R/(R + 2R_{cal})][(R + 3R_L + 2R_{cal})/(R + 2R_L)]$$

$$= [1/(1 + 2R_L/R)][1 + (3R_L)/(R + 2R_{cal})]$$

Since $3R_L/(R + 2R_{cal})$ is extremely small compared to the value of 1, then this term drops out and the simplified equation becomes:

[12] $$e_o/e_o' = 1/(1 + 2R_L/R)$$

Using the above equation the output from the bridge can be normalized or corrected by multiplying the measured output by a factor of $[1/(1 + 2R_L/R)]$ i.e.,

[13] $$e_o = e_o'[1/(1 + 2R_L/R)]$$

Example:

From the above equations, the estimated outputs can be calculated for various blade stations on Aquilo and an R_{cal} of 114.2 kΩ (250 με). Note that the normal output should be 2.626 mV (R_L = 0).

The first column in Table 3, Station Group, refers to the various areas where strain gauges are located on Aquilo (Figure 3). The second column refers to the corresponding lead resistance of these gauges. The third column in Table 3 lists the output for a real strain of 250 με if there is no lead resistance. The outputs illustrate the error encountered because of this lead resistance. All the outputs would be 2.626 mV if the lead resistance was zero. Column five lists this error as a percentage. The last column illustrates what occurs if R_{cal} is used to adjust circuit gain without taking into account lead length resistance. This is normal practice in systems with extremely low lead resistance, but causes large errors when the procedure is followed where lead resistance is significant. The shunt resistor is switched in to simulate a value of strain. The gain is then adjusted to this known value. However, the output is much higher with lead resistance present even though in reality actual strain output will be less than if no lead resistance is present. Thus errors are compounded. The last column illustrates the resulting compound error in the measurement.

Table 3. R_{cal} errors due to lead length on Aquilo

Station group	R_L (Ω)	Output e_o 250 με strain (mV)	Output e_o R_{cal} (250 με) (mV)	Error R_{cal} for 250 με (% error)	R_{cal} gain error (% error)
1	2.3	2.529	2.726	3.82	7.79
3	1.9	2.545	2.709	3.17	6.44
4	1.3	2.570	2.683	2.18	4.40
5	0.7	2.595	2.656	1.15	2.35
6	0.7	2.595	2.656	1.15	2.35
7	0.2	2.617	2.634	0.32	0.65

Table 3 shows that R_{cal} can be a very poor method of calibrating the system if lead resistance error is not taken into account.

7.3 Temperature Effects on Lead Resistance

The lead resistance, which is a major cause of strain gauge errors, changes value with temperature. The lead resistance will decrease about 8% per 20°C decrease in temperature. This is a difficult error to correct

for, expecially with respect to R_{cal}. For normal strain measurements, monitoring V_{ex} using a six-wire system eliminates this problem but does not eliminate the total error in the R_{cal} measurement. (In this measurement $2R_L/R$ error is caused by the lead resistance in the V_{ex} lines while a further $2R_L/R$ error is caused by lead resistance in the shunt resistor lines.)

However, the temperature effect is a second-order effect and in almost all cases it is very small.

Example:

If the nominal lead resistance R_L is 6 Ω and the bridge resistance R is 120 Ω, then the resulting output error is $-2R_L/R$ or -10%. The resulting R_{cal} error is $2R_L/R$ or +10%. Assuming the above calculations are corrected for 20°C, then the resultant error at 0°C would be as follows:

$R_L = 6\ \Omega\ @\ 20°C$

$R_L = 6 \times 0.92 = 5.52\ \Omega\ @\ 0°C.$

[14] Temperature output error = $2\Delta R_L/R = 0.96/120 = 0.8\%$

where

ΔR_L = change in lead resistance from 20°C

Temperature effects on lead resistance also introduce errors in R_{cal}.

[15] R_{cal} error (temperature dependent) = $2\Delta R_L/R = 0.96/120 = 0.8\%$

From the above example it is easily seen that temperature effects on both the strain output and the R_{cal} output are fairly small.

Example: Aquilo

On the Aquilo installation the largest lead resistance is about 2.3 Ω. Using equation [16], the error at 20°C would be about 3.8% for group #1 (see Table 3). If the measurement was then taken in the winter at say -10°C, the resultant error would be decreased to about 3.4%. Assuming the error is corrected for 20°C, then the resultant error for R_{cal} would be 0.45% and 0.23% for actual strain measurements.

Lead resistance errors can be reduced drastically by two methods which can be seen by looking at the error formulas.

[16] Output error = $-2R_L/R$

[17] R_{cal} error = $+2R_L/R$

From the above equations, this error can be reduced either by increasing the bridge resistance and/or by decreasing the lead resistance. Bridge resistance can be increased by selecting higher resistance gauges (i.e., 350 Ω rather than 120 Ω gauges) to do the measurement. Lead resistance can be reduced by using heavier wire for measurements (thus reducing resistance) or by moving R_{cal} and the measurement electronics closer to the bridge.

Example: Aquilo

The longest bridge lead on Aquilo was 120 ft of #24 stranded wire. This represents an R_L of about 2.3 Ω. If the wiring had been installed with #20 stranded wire, the lead resistance, R_L, would be roughly one half or 1.15 Ω. The resultant R_{cal} error would go from 3.8% to 1.9%. In addition, if 350 Ω gauges were used the resultant error would be reduced from 3.8 to 0.65%.

7.4 Multi-fed Bridges

Much higher errors due to lead resistance occur if the excitation currents for more than one bridge are run on the same lines. This creates an error greater than that of a single bridge with its own excitation voltage.

In general, the paralleling of bridge power lines can be extremely risky with respect to both reliability and errors.

As discussed before, the output error due to lead length is a factor of $2R_L/R$. For each additional bridge connected to the same power lines this error increases directly.

[18] Output error = $2R_LN/R$

where

N = number of bridge circuits connected to the same set of excitation leads

The R_{cal} error is affected the same way. The shunt resistant lead error $2R_L/R$ is not affected by the number of bridges paralleled so that the resulting error is as follows:

[19] R_{cal} error = $+2(N + 1)R_L/R$

Example

The maximum cable run on the Iles de la Madeleine VAWT was 165 ft of #22 wire, which is about 2.7 Ω at 20°C. The number of bridges paralleled was four. This gives an R_{cal} error of about 22.6% due to R_L resistance. The above value also changes about 3% per 20°C due to temperature effects on the cable.

8.0 APPLICATION TO A BRIDGE CIRCUIT SIMULATOR AND TO A 500 kW VAWT (AQUILO)

In this section the above calculations for strain gauge outputs along with their errors are compared to actual measurements on both the Aquilo machine and on a bridge simulator. The actual values of components used on Aquilo are given and the various calculations performed are illustrated. The bridge simulator comprises four 0.01%, 120 Ω resistors connected in a bridge configuration. This bridge was then connected to 100 ft of #22 wire to provide lead length error.

8.1 Measurements on the Bridge Circuit Simulator

Various measurements were made on the circuit to confirm calculations with actual measurements. Actual lead resistance measurements, R_L, averaged 1.51 Ω. These resistances ranged from 1.45 to 1.54 Ω. The exitation voltage, V_{ex}, was measured at 10.002 V. The bridge was balanced first using a shunt resistor. R_{cal} for the test was measured at 119 879 Ω.

Results

(1) The output voltage with no lead resistance in the circuit ($R_L = 0$) was measured at 2.506 mV. Using equation [13] the output was calculated to be 2.501 mV.

(2) With the lead resistance only in the excitation lines, the output should reduce by a factor of $R/(R + 2R_L)$. The measured output was found to be 2.443 mV. The calculated output was 2.444 mV.

(3) With all lead resistances in and R_{cal} shunted at the far end of the wire from the bridge, the output should increase by a factor of $(R + 2R_L)/R$. The calculated output should increase to 2.569 mV. The actual output was measured at 2.565 mV.

The above results confirm the calculations. Calculated outputs compared with measured results to within a few microvolts.

8.2 Measurements on AQUILO

The R_{cal} value chosen on Aquilo was the closest value available to offset the bridge an equivalent of 250 με. The value chosen was a 121 kΩ, 1%, 200 ppm/°C resistor.

First, the ideal output with no lead resistance was calculated for this shunt resistor value.

[20] $$e_o = (V_{ex}/2)(R)/(R + 2R_{cal})$$

where

$$R_{cal} = 121K\ \Omega$$
$$V_{ex} = 10.0$$
$$R = 120\ \Omega$$

Therefore,

$$e_o = 2.478\ mV$$

This is equivalent to the following microstrain.

[21] $$\frac{e_o}{e_{250}} = \frac{\varepsilon_o}{250}$$

where ε_o = equivalent strain (με) for e_o. Therefore,

$$\varepsilon_o = 250 \times \frac{2.478}{2.626} = 235.9\ \mu\varepsilon$$

i.e., the με equivalent for a 121 kΩ shunt resistor was found to be 235.9 με.

The predicted output can now be calculated using the estimated lead resistance and equation [13].

Table 4 shows the values calculated for e_o using the known lead resistances and R_{cal}'s at various stations on Aquilo. Along with these values, the actual measurements are also shown. The calculated output for R_{cal} with no lead resistance was 2.478 mV.

The calculated error and the measured error show some difference, for the following reasons.

(1) The temperature during measurement was at -10°C, which would cause possible gain errors in the amplifiers which would cause output errors.

Table 4. Comparison of measured with calculated error due to lead length

Station group	Estimated lead resistance R_L	Estimated output R_{cal}=121 kΩ	Actual measured output R_{cal}=121 kΩ	Measured error (%)	Value of $2R_L/R$ (%)
A1	2.3	2.67 mV	2.59	4.4	3.8
A3	1.9	2.63 mV	2.55	2.8	3.15
A4	1.3	2.56 mV	2.53	2.0	2.15
A5	0.7	2.54 mV	2.50	0.8	1.15
A6	0.7	2.54 mV	2.50	0.8	1.15
A7	0.2	2.49 mV	2.48	0.4	0.35

(2) The resistors used for R_{cal} are 1%, 200 ppm/°C precision resistors. The lead resistances were found typically to vary more than 10% for the same length of wire. This would cause differences in the various outputs.

(3) Readings were taken with some wind which caused noise on the measurements which could bias some of the readings.

(4) The measurement results are within the error band of the measurement devices.

Although there is some difference in the calculated errors and the errors actually measured, they substantially confirm the calculations.

9.0 ERRORS CAUSED BY PROTECTION CIRCUITS

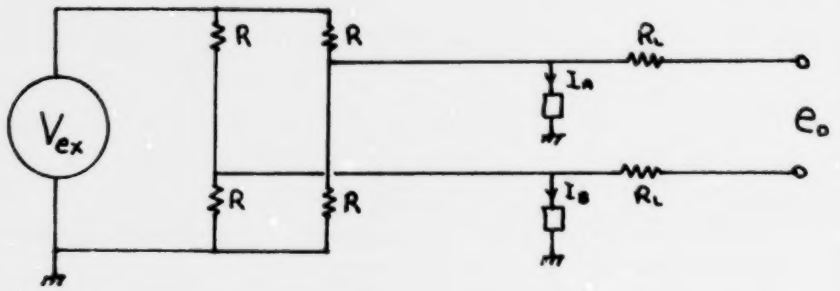
Protection circuits are often employed in turbine electronic circuits to protect the data acquisition system from lightning strikes. These devices are constructed to break down at a known voltage level and shunt high currents to ground away from the data acquisition system. Reference 2 explains the operation of these devices.

Varistors and zener diodes are common devices used for this protection. Both are semi-conductor devices which immediately implies they have a leakage current at normal operating voltages.

The typical leakage current for varistors is 20 μA. The typical leakage current for zener barrier circuits is 10 μA (but it varies with temperature). If these circuits are installed before amplification, complications in the measurements can occur. This can best be illustrated through an example.

Example:

The following strain gauge circuit is protected using varistors. One has a leakage current of 10 μA while the other has a leakage current of 40 μA. The bridge used is a standard 350 Ω. The circuit is as follows:

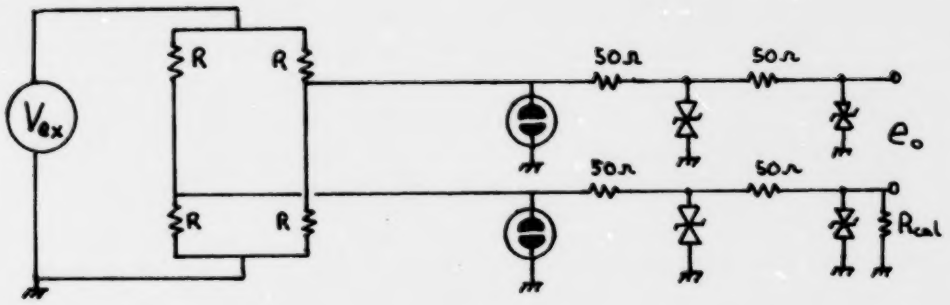


$$e_o = R(I_A - I_B)$$
$$= 350(10 - 40) \times 10^{-6}$$
$$= -10.5 \text{ mV}$$

From the above calculations it can be seen that the output from the bridge can be drastically affected by the introduction of varistor protection. Offsets can easily exceed 200% of normal full scale output. Since the leakage current changes with temperature, the output of the bridge will change with temperature. Although the dynamic error and overall error over a short time is small, the dc offset instability will cause lost time and effort in the measurement process, i.e., correcting offsets each day. In conclusion, it is better in most cases to amplify before protection. This avoids a lot of unknown effects of the strain gauge outputs, but does endanger the amplifier circuits.

Another problem encountered with lightning protection using barrier circuits is the resistance introduced into the circuit. A standard zener barrier circuit has two resistors of about 50 Ω (typical) in the measurement line. Typical leakage current is about 10 μA for the diodes. If the barrier is installed before any active electronics, the R_{cal} error becomes a huge problem. It would be prohibitive to have 100 Ω in series with the R_{cal} shunt resistor. The zener leakage current also inhances the problem with the R_{cal} measurement.

Example:



If R = 120 Ω and R_{cal} = 112 kΩ, the normal output (no barrier) with R_{cal} in the circuit is 2.677 mV. With the zener barrier circuit in place there is a voltage drop across the 50 Ω resistors. Assuming the measurement system has an infinite input impedance and R_{cal} is out, the voltage drop across the resistors will be about 0.8 mV. Although each side of the bridge is connected to the barrier, which somewhat cancels these errors, a problem can still occur since the diode leakage is substantially different with each diode and the leakage current changes at different rates (since the device is non-linear), with respect to temperature and voltage. If R_{cal} is now placed in the circuit, the output will measure 4.9 mV or 183% of the value without the barrier in (and this assuming the diode leakage current has been balanced for each arm). The two 50 Ω resistors act in the same manner as lead length error (see Section 7.0).

The conclusion is simple. Barriers cannot be placed between a calibration resistor R_{cal} and the bridge. Also, barrier circuits are not recommended on low level signals since leakage current presents too many possibilities of error and drift problems. It is usually better to amplify the signal first and then install protection devices to before the data acquisition system. The amplifiers might be lost during a lightning strike but with proper design they would be easily replaced.

10.0 CONCLUSIONS

These notes illustrate that errors do exist in strain measurements but they can be reduced dramatically by using care in the purchase and installation of the gauges. The following lists some of the methods which can reduce the chance of large errors.

(1) Wherever possible use large resistance gauges; 350 Ω or even 1000 Ω gauges are excellent.

(2) Use care and caution when installing the gauges. Water penetration in the gauge area or poor heat dissipation on dummy gauges can cause error in the measurements or failure of the sensors.

(3) Keep lead lengths as short as possible and of low resistance. Use heavier wire wherever possible.

(4) Use low temperature coefficient R_{cal} and gain resistors to reduce errors from temperature changes.

(5) Use one set of leads to excite each bridge. This makes the system both more reliable and more accurate.

(6) Purchase gauges in same-batch lots so that their characteristics are better matched. This reduces the chance of large mismatch errors.

(7) Install protective devices such as varistors or zener barriers after amplification of low level signals.

If all of the above recommendations are followed in the instrumenting of a turbine, there should be little problem which strain measurement errors.

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